

Mass hierarchy and energy scaling of the Tsallis–Pareto parameters in hadron productions at RHIC and LHC energies

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Abstract. The latest, high-accuracy identified hadron spectra measurements in high-energy nuclear collisions led us to the investigation of the strongly interacting particles and collective effects in small systems. Since microscopical processes result in a statistical Tsallis–Pareto distribution, the fit parameters q and T are well suited for identifying system size scalings and initial conditions. Moreover, parameter values provide information on the deviation from the extensive, Boltzmann–Gibbs statistics in finite-volumes. We apply here the fit procedure developed in our earlier study for proton-proton collisions [1, 2]. The observed mass and center-of-mass energy trends in the hadron production are compared to RHIC dAu and LHC pPb data in different centrality/multiplicity classes. Here we present new results on mass hierarchy in pp and pA from light to heavy hadrons.

1 Introduction

In high-energy nuclear physics the investigation of small colliding nuclear systems is fundamentally important for understanding collective effects. Strong correlation phenomena typical for heavy-ion collisions were recently observed in pp and pA collisions [3, 4]. While correlations in such small systems are more clearly observable thanks to the lower background, their statistical and thermodynamical description points towards to exceed the classical Gibbs–Boltzmann framework. A modern tool for such studies is provided by the non-extensive statistics. In the application one fits Tsallis–Pareto-type distributions to describe the measured spectra in wide central-of-mass energy and p_T ranges [5–8]. In our recent works [1, 2], we analyzed the spectra of various hadron species in pp collisions from RHIC to LHC energies. We compared the results to theoretical model calculations and explored the mass hierarchy and c.m. energy scaling of the parameters. In this short contribution, we extend our investigations to the latest identified strange- and heavy-flavored hadron spectra measured in dAu and pPb collisions from $\sqrt{s_{NN}} = 200$ GeV RHIC to $\sqrt{s_{NN}} = 5.02$ TeV LHC energies in different centralities. We used data from STAR [11] and ALICE [12, 13] measurements and analyzed them following the procedure described in details in Refs. [1, 2].

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2 Identified hadron spectra from pA collisions

Recent high-precision measurements in dAu and pPb collisions at RHIC and LHC energies present a *Janus-face* behavior, depending on the multiplicity class of the selected data set. While low-multiplicity events are more jet-like, the high multiplicity ones include correlations and present sizeable nuclear modification, especially at the low- and intermediate momentum ranges. The same duality has been already observed in nucleus-nucleus (AA) collisions [14–16]. In smaller systems it is a special challenge to identify these components [17]. We quantify and separate these observations and deduce the parameters of the microscopical interactions. We apply the same formula as in Refs. [1, 2], for all centrality classes (0-20%, 20-40% and 40-100% for the STAR data, 0-5%, 5-10%, 10-20%, 20-40%, 40-60%, 60-80% and 80-100% for the ALICE data):

$$\frac{d^2N}{N_{ev}2\pi p_T dp_T dy} \Big|_{y \approx 0} \sim \left[1 + (q-1) \frac{m_T}{T} \right]^{-\frac{1}{q-1}}. \quad (1)$$

Here, $m_T = \sqrt{p_T^2 + m^2}$ is the *transverse mass* of the given hadron species. We note that this formula can be derived from the Tsallis q -entropy and, as we pointed out in Refs. [6, 18], the parameters carry a certain physical meaning: the *non-extensivity* parameter, q measures the deviation from the (extensive) Boltzmann–Gibbs state ($q = 1$), while a generalized temperature-like parameter, T provides a temperature value taking into account the finite-size effects and fluctuations. These parameters are interconnected via the multiplicity distribution, e.g. a (negative) binomial distribution [19]. On Fig. 1

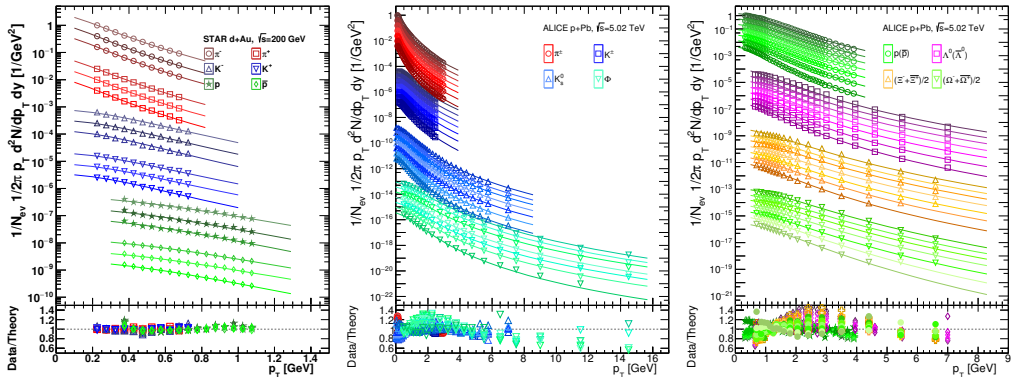


Figure 1. The fitted spectra for various identified hadrons measured in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR, RHIC (*left*) and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at ALICE, LHC (*middle panel for mesons and right panel for baryons*). Data have been scaled for better visibility. *Bottom panels* present the Data/Fit ratios using the same color as on the spectra.

the analyzed identified hadron spectra measured in small colliding systems along with the fitted distributions were plotted. For both the $\sqrt{s_{NN}} = 200$ GeV dAu at RHIC and $\sqrt{s_{NN}} = 5.02$ TeV pPb at LHC energy collisions we extracted the parameters of Eq. (1) utilizing the ROOT data analysis framework, performing fits based on the minimal χ^2 method. Based on the available identified hadron data published in Refs. [11–13], the fits were performed in various centrality bins on as wide p_T ranges as possible. Lower panels present the data-to-fit ratios with agreement of 20% and 40% – 50% for dAu (RHIC) and pPb (LHC) data respectively.

3 Results: parameters and mass hierarchy, compared to pp

The fit parameters of Eq. (1) are plotted on the parameter-space diagram, Fig. 2. T is plotted against $q-1$, with the latter measuring the deviation from the Boltzmannian case directly. The empty markers and the shaded area show the pp results with different energies ($62.4 \text{ GeV} \leq \sqrt{s} \leq 7 \text{ TeV}$) as it was presented in Ref. [1] along with the STAR dAu data at $\sqrt{s_{NN}} = 200 \text{ GeV}$. The full markers show the parameters from the present fit for the pPb spectra at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. The new points that

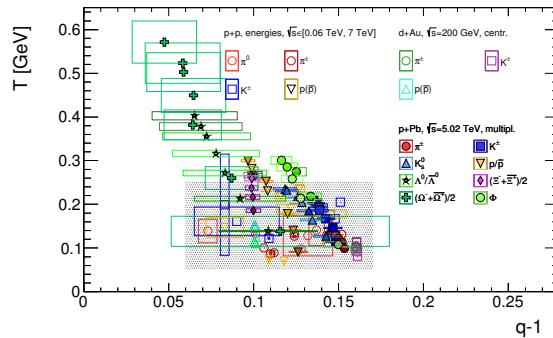


Figure 2. The T vs $(q - 1)$ parameter space for identified hadron spectra in pPb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ with different multiplicity classes (*filled markers*) and for the same pp measurements for various \sqrt{s} energies from Ref. [1] including dAu STAR data [11] at $\sqrt{s} = 200 \text{ GeV}$ (*empty markers and shaded area*).

are consistent with the previous results (i.e. those inside the shaded box) are the most pp-like points, especially for the smallest multiplicity class. We observe deviance only for those points which are extracted from high-multiplicity spectra. Increasing the multiplicity either by increasing the c.m. energy or getting to more central events, lead to both higher q and T . Points in the parameter space originating from datasets with similar multiplicities group together nicely. The dAu data from STAR accompany the lowest energy pp fit parameters. It is either due to the low multiplicity or due to the very limited p_T range of the identified transverse momentum spectra. The absence of strong power-law tail results in a weak determination of the Tsallis – Pareto parameters. Fig. 2 also represents the mass hierarchy: the higher the mass of the identified hadron, the higher the T and the lower the q is. This effect is more visible on Fig. 3, where the q (*left panel*) and T (*right panel*) parameters are plotted for each identified hadron species in order to analyze the mass hierarchy effects. Here we used the same markers as on the figures above. This result extends our earlier analysis in pp collisions in Refs. [1, 2] using only π , K , and $p(\bar{p})$, while adding the hadron species with higher masses, we can see a mass hierarchy for both parameters. Based on the extracted parameters, the hadron species with the highest mass has the highest T , meanwhile the non-extensivity is reduced as $q \rightarrow 1$, especially for the low multiplicity events. Trends with growing s quark content supports the idea of strangeness enhancement [3]. It can be a signature of the quark-gluon plasma like, close-to-thermalized, hot and dense matter in small colliding nuclear systems like pp, dAu, or pPb.

4 Summary

Mass and strangeness hierarchy is analyzed and presented for pp, dAu, and pPb collisions. We analyzed data in a wide $\sqrt{s_{NN}}$ range from RHIC to LHC energies in various centrality/multiplicity ranges. The results are consistent with our previous center-of-mass energy scaling investigations for the most pp-like, peripheral centrality classes, however deviations are observed for central (c.f. high multiplicity) collisions for hadron species with high mass. Our main observation is that the measure of the

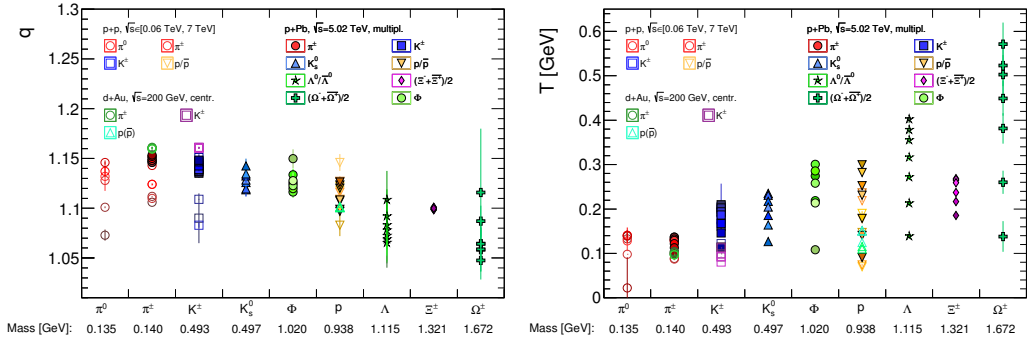


Figure 3. The fitted Tsallis–Pareto parameters q (left panel) and T (right panel) obtained in pp, dAu, and pPb collisions for all investigated hadron species in increasing mass order.

non-extensivity, $q - 1$, decreases with increasing hadron mass, thus higher-mass hadrons present less deviation from the Boltzmann–Gibbs $q = 1$ case. On the other hand, similar to the exponential fits, higher-mass hadron species require higher T to obtain the best fit results.

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